STATUS OF THE VEPP-4M COLLIDER

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Abstract

Since 2004, the principal high-energy physics experiment carried out at the VEPP-4M electron-positron collider is precise measurement of the τ-lepton mass. Moreover, a series of experiments to improve measurement accuracy of the J/ψ, ψ(2s) and ψ(3770) mesons has been performed. During all the high-energy physics experiments, absolute calibrations of beam energy by the resonant depolarization method and routine energy monitoring using the Compton back-scattering technique were realized. Monitoring of beam energy spread, which is also important, was implemented using several techniques. To provide the VEPP-4M high performance, some investigation and further development of the machine have been done, the most important results are described.

HIGH-ENERGY PHYSICS EXPERIMENTS

Since 2004, the VEPP-4M electron-positron collider [1] is operating for high-energy physics experiments in the 1.5-2.0 GeV energy range. The most important of them is precise measurement of the τ-lepton mass at the producing threshold. The τ-lepton mass together with the lifetime and the decay probability to $e\bar{\nu}_e\nu_\tau$ can be used to test the $\mu-\tau-$universality principle which is one of the postulates of the Standard Model.

A series of experiments to improve measurement accuracy of the J/ψ, ψ(2s) and ψ(3770) mesons has been also performed. The measured masses are:

$$M_{\psi(2s)} = 3686.117 \pm 0.012 \pm 0.015 \text{ MeV}$$
$$M_{\psi(3770)} = 3773.5 \pm 0.9 \pm 0.6 \text{ MeV}$$

Measurement accuracy reached in these experiments is 2 times better than the world average value for ψ(2s), and 3 times better for ψ(3770). There are only 5 particle masses (e, p, n, μ, π) measured with better accuracy.

Precise measurements of the J/ψ and ψ(2s) meson masses provide the energy scale in the range around 3 GeV which is a basis for accurate determination of masses for all charmed particles. These measurements are also important for the accurate determination of the τ-lepton mass.

During 2004-2006 runs, total luminosity integral is 11.28 pb^{-1} (1.75 pb^{-1} in 2004, 4.51 pb^{-1} in 2005, and 5.03 pb^{-1} in 2006). Fine adjustment of the accelerator at low energy parallel with improving of the machine reliability result in gradual increase of average luminosity. The luminosity production rate is shown on Figure 1.

For the τ-lepton mass measurement, a procedure of regular particle energy calibration is essential. Absolute energy calibration is realized by the resonant depolarization method [2], between data collection runs of the KEDR detector. During the runs, routine energy monitoring is carried out using the Compton back-scattering technique [3]. Figure 2 shows an example of the energy monitoring during one-week interval of the scan in the vicinity of ψ(3770) meson.

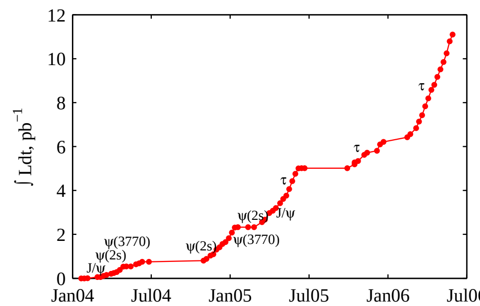

Figure 1: Luminosity integral 2004-2006.

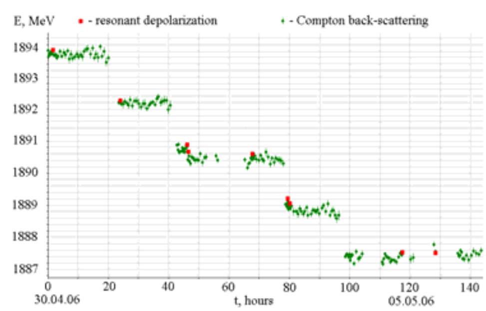

Figure 2: Energy monitoring in the vicinity of ψ(3770).

ENERGY SPREAD MEASUREMENT

In the experiment of the τ-lepton mass measurement, it is important to know beam energy spread for evaluation of its contribution into the total systematic error of the τ-lepton mass. Routine energy spread monitoring during high-energy physics experimental runs is provided by the Compton back-scattering method, but accuracy of the method now is not better than 15-20%. The energy spread is measured more accurately by scan of the ψ(2s) meson peak, but this procedure is time-consuming and can not be repeated frequently.

Several methods of energy spread measurement are realized at the VEPP-4M [4]. Two methods are based on analysis of chromatic synchro-betatron harmonics of coherent betatron oscillation excited by a short kick. For non-synchronous particles, machine chromaticity introduces a betatron frequency shift. This effect causes beating in the oscillation envelope and synchrotron sideband peaks in the oscillation spectrum. In the first method, the amplitude ratio of synchrotron satellites to the main betatron peak is measured in dependence of chromaticity. Fitting this ratio dependence with the theoretical one gives the energy spread value. In the second method, energy spread is calculated by fitting the measured oscillation envelope with the theoretical curve.

Energy spread was measured using both methods for a set of the VEPP-4M operation modes with different energy and energy spread values. The measurements were done with the small beam current of $10 \div 50\ \mu A$, when collective effects are negligible. Chromaticity was changed with sextupole magnets and evaluated from the measured betatron tune dependence of the RF frequency. Turn-by-turn beam position was measured using fast photomultiplier tube. Figure 3 shows an example of measured data with the theoretical envelope (upper plot), and its amplitude spectrum with the noticeable synchro-betatron peaks up to 3-rd order (lower plot).

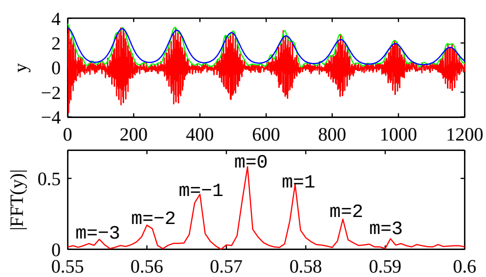

Figure 3: Synchro-betatron harmonics, $\xi_y = 18$.

High-energy physics experiments were performed with the beam current close to beam-beam effects limit of $1.5 \div 3.5$ mA per bunch, depending on the beam energy. Current dependence of the energy spread was evaluated using measured bunch lengthening and grows of the horizontal bunch size.

Energy spread measurements performed by all three methods conform to results of the J/ψ scan at the 1548 ± 10 MeV energy performed in 2002. There is also a good agreement of these measurements with the 2005-2006 ψ(2s) scan at the 1843 ± 10 MeV energy.

TEMPERATURE MEASUREMENT AND STABILIZATION

Temperature Monitoring System

Specific character of the high-energy physics experiments realized at the VEPP-4M is the high-precision beam energy evaluation required. To a first approximation, beam energy is proportional to the dipole magnetic field integral. On-line monitoring of the magnetic field with 10^{-6} accuracy is realized by nuclear magnetic resonance (NMR) method. But the beam energy also depends on thermal expansion of the magnets and tunnel. For accurate estimation of the beam energy between resonance depolarization calibrations, an empirical formula has been found. This formula provides the energy estimation with 20 keV accuracy using the magnetic field measured by NMR, and temperature of the magnets, tunnel walls, cooling water, etc.

Thus, it became necessary to measure precisely temperature in a lot of locations of the VEPP-4M facility. For this goal, a new system of temperature monitoring is developed [5]. This system is based on High-Precision Digital Thermometers DS1631 with the resolution of $0.0625°$C and absolute accuracy of $0.5°$C in the $0 \div 70°$C temperature range.

To control the DS1631 sensors and to transfer measured data to the VEPP-4M control system, 32-channel controller was developed in BINP. The controller inquires all the connected sensors every second and writes data to the internal memory. To read/write, store and visualize data of all the controllers installed at the VEPP-4M, a special program runs in a computer included in the VEPP-4M control system. Relay interlock function to prevent overheat is also implemented to the controller, up to 12 solid-state relays can be used in one controller. The control program reads from and writes to each controller specifications for the relay contact closure then the controller closes relay contacts automatically, if the temperature is out of the specified range.

Thermostabilization of the Magnets

During the J/ψ- and ψ(2s)-meson experiments, there is not only a demand for high absolute definition of the energy but also for its high stability (better than 10^{-5}). Continuous temperature monitoring shows considerable diurnal and seasonal variations of the VEPP-4M magnets temperature, which cause beam energy variation up to 80 keV/°C. For the VEPP-4M magnets, a double-loop water cooling system is used. The magnets are cooled by circulating distillate which is cooled by service water in a heat exchanger. Temperature of the service water depends on many external factors such as ambient temperature, atmospheric humidity, cooling condition in a cooling tower, etc. All these uncontrollable factors result in quite big diurnal and seasonal variations of the service water temperature.

To stabilize temperature of the VEPP-4M magnets, a system of distillate thermostabilization has been developed. A computer-controlled valve was installed at the service water input of the heat exchanger. Temperature of the distillate and service water is measured permanently by high-precision thermal sensors installed on the heat exchanger input and output. A control program analyzes the data measured and regulates the service water flow and therefore heat-transfer rate. Figure 4 illustrates efficiency of the system. There are results of one day monitoring of the distillate (upper plots) and the service water (lower plots) temperature. The left pair of plots corresponds to the ther-

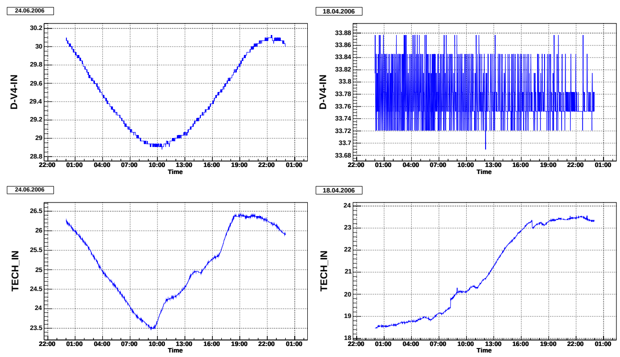

Figure 4: Magnets' distillate thermostabilization.

mostabilization off, the right one corresponds to the thermostabilization on. One can see that without thermostabilization 3-degree variation of the service water temperature leads to 1.2-degree variation of the distillate temperature, whereas thermostabilization system keeps the distillate temperature stable within 0.1 degree while the service water temperature has 5-degree variation.

Thermostabilization of the RF-cavities

Since 2004, the VEPP-4M collider operates in the $2 \times 2-$bunch mode. It allows us to increase the luminosity, but a problem of longitudinal instability appears. Unstable phase oscillation occurs due to parasitic high-order modes (HOM) of the VEPP-4M RF cavities. This instability is one of the main efficiency decreasing factors, because it reduces luminosity drastically. High-amplitude phase oscillation leads to particle loss and can be dangerous for the KEDR detector.

Each of 5 RF cavities is equipped by three mechanical remote-controlled HOM suppressors. Fine tuning of these suppressors allows us to find stability regions of longitudinal beam motion. But the cavity temperature variation results in the cavity deformation and then leads to a shift of working conditions away from the stability regions. To stabilize the RF cavity temperature, automatic heaters of cooling water have been developed [6]. Temperature is measured by thermo-sensors with a sensitivity of 10 mV/°C. For each RF cavity, 5 kW flowing water heater is switched on/off by controllable electronic switches. Temperature analysis and power control is provided by a microcontroller.

Using of the thermostabilization system, temperature variation of the RF cavities have been reduced from 5°C down to 0.2°C. As a consequence, probability of excitation of the phase oscillations is reduced more than in 100 times.

FAST TRANSVERSE FEEDBACK

Maximal bunch current in the VEPP-4M collider is limited by the transverse mode coupling instability (TMCI or fast head-tail). At the 1850 MeV energy, threshold current is about 10 mA. This effect is well-studied both analytically (two-particle model, hollow-beam model, Vlasov equation, etc.) and numerically. To suppress the instability, feedback is the convenient way. According to the theory, pure resistive feedback is unable to suppress this instability, and there are strict tolerances of the reactive feedback. Experiments confirm the theoretical predictions in relation to the reactive feedback, but it was found the resistive feedback also can work.

For the resistive feedback, conditions of applicability was studied in [7]. For the head-tail instability, positive chromaticity kills 0-th oscillation mode, i.e. makes bunch center of mass stable, but other oscillation modes are unstable, negative chromaticity has inverse effect. The idea is to suppress 0-th oscillation mode using resistive feedback, while to keep other modes stable due to negative chromaticity. Calculation based on the hollow-beam model shows that it is possible to exceed the instability threshold 3-5 times.

According to this investigation, transverse bunch-by-bunch feedback system is now under commissioning at the VEPP-4M. Beam signals are measured by two sensitive strip-line BPMs to have information both of the beam position and momentum. Then digitized data is processed by a DSP, which calculates an amplitude of short pulse kick for each bunch. These pulses are converted by digital-to-analog converters and amplified by 200 W wide-band power amplifiers. 1.9-meter long electrostatic separators used as the kickers allows to reduce maximal required voltage of the kick pulse. At present, all the electronics for one feedback channel is designed, produced and installed at the VEPP-4M, first beam measurements have been done. The system description and the experimental results are presented in [8].

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